

Diffusion Driven Desalination-- An Innovative Approach to Fresh Water Production from Seawater

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Motivation for Developing Technology

- Fresh water is a commodity in diminishing supply
- Conventional water distillation plants are energy Intensive, and fresh water product is expensive
- There exist many industrial processes that produce waste heat that is discarded to the environment; waste heat may be utilized to produce fresh water
- Ideal technology will utilize waste heat to produce fresh water and deliver large production rate with low energy consumption



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World Water Supply

- Fresh water resources have been steadily on the decline since the 1950's
- 96% of the world's water supply is saline or brackish
- There exist more than 7500 desalination plants in operation worldwide
- Saudi Arabia operates the largest desalination plant with a capacity of 128 MGD
- United States accounts for 12% of world's desalination capacity--majority of production in Caribbean and Florida



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Conventional Desalination Technologies

- Reverse Osmosis

- Distillation

- Flash Evaporation

- Solar Still

- Humidification/Dehumidification

- Critical Pressure

- Electrodialysis

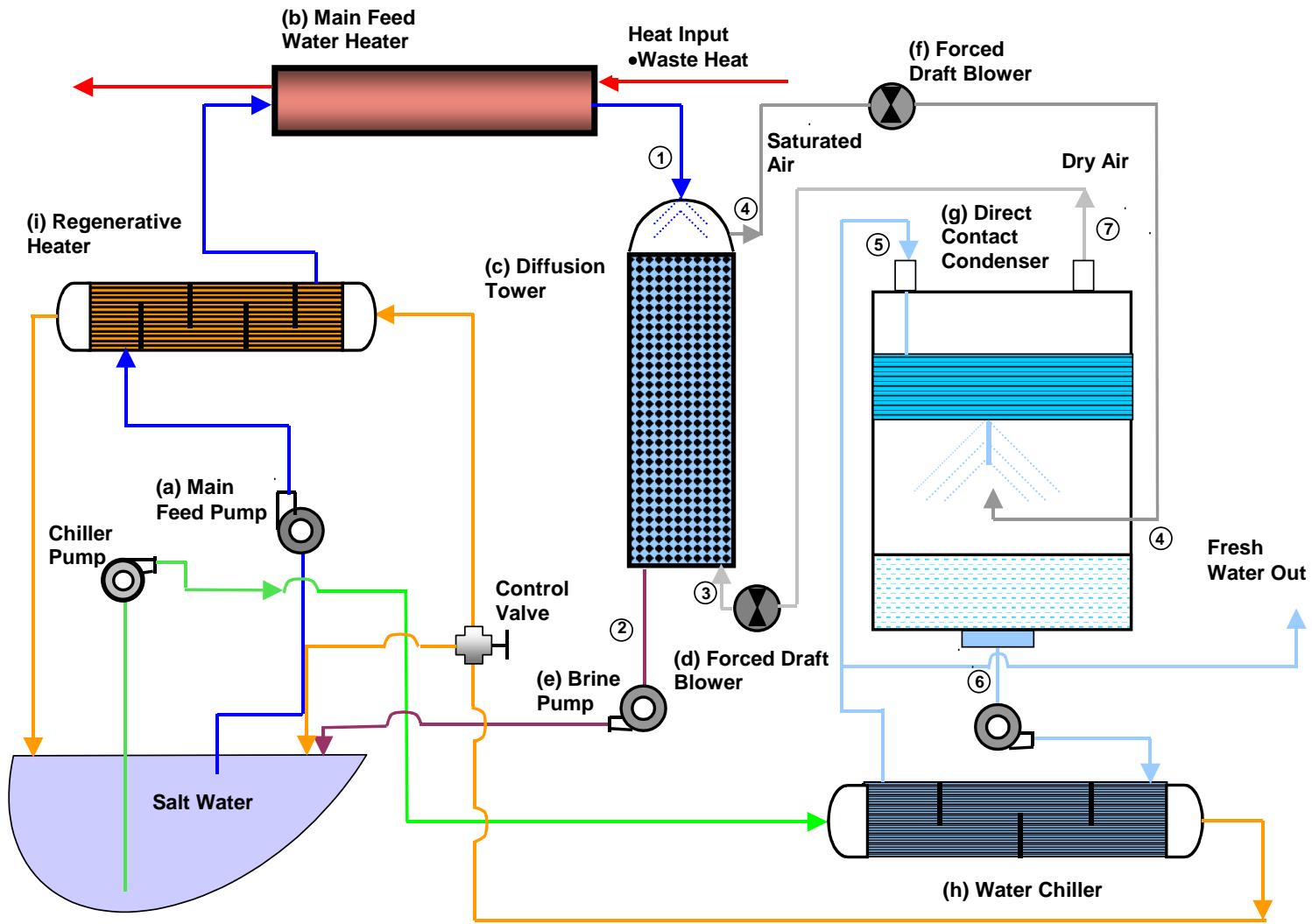
- Direct Freezing



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University of Florida Diffusion Driven Desalination Process



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Advantages of Diffusion Driven Desalination

- Waste heat may be used to produce fresh water
- Temperature requirement for heated water is as low as 45 C
- Low energy consumption process when integrated with a power plant
- Low temperature process; inexpensive materials of construction and waste heat from many different sources is useful for fresh water production
- Very large production rates possible; waste heat from a 300 MW power plant can produce 4.5 million gallons of fresh water per day



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Best Utilization of Diffusion Driven Desalination



Diablo Nuclear Power Plant,
San Luis Obispo

I. Replace Cooling Towers at Power Plants With Desalination Plant

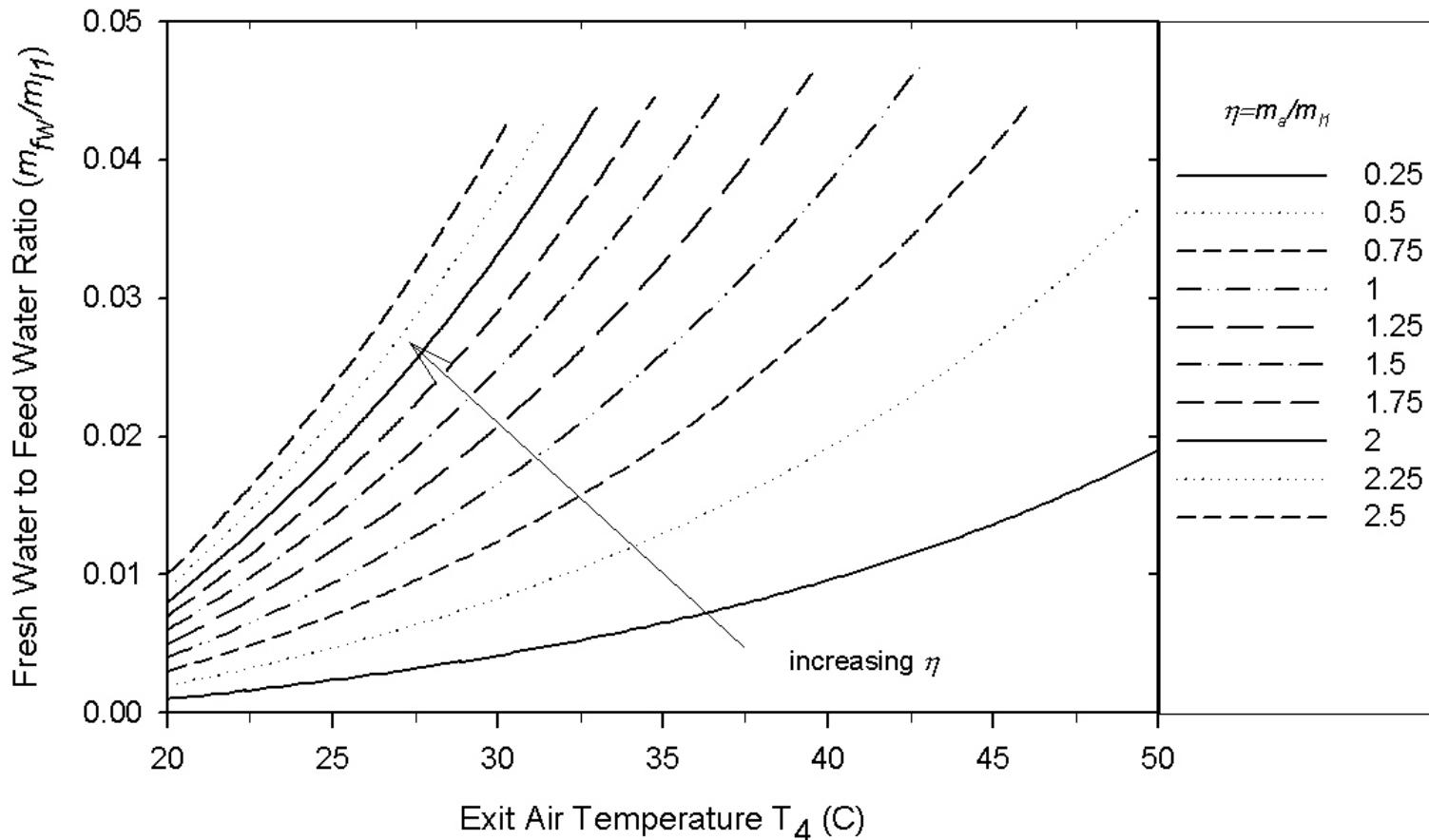
- Many electric power generation plants are sited along the coastline
- Power plants discharge waste heat into the environment via cooling towers or direct discharge into the sea
- Utilize waste heat to produce fresh water



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DDD Process Performance

Fresh water production efficiency for $T_H=50^\circ \text{ C}$

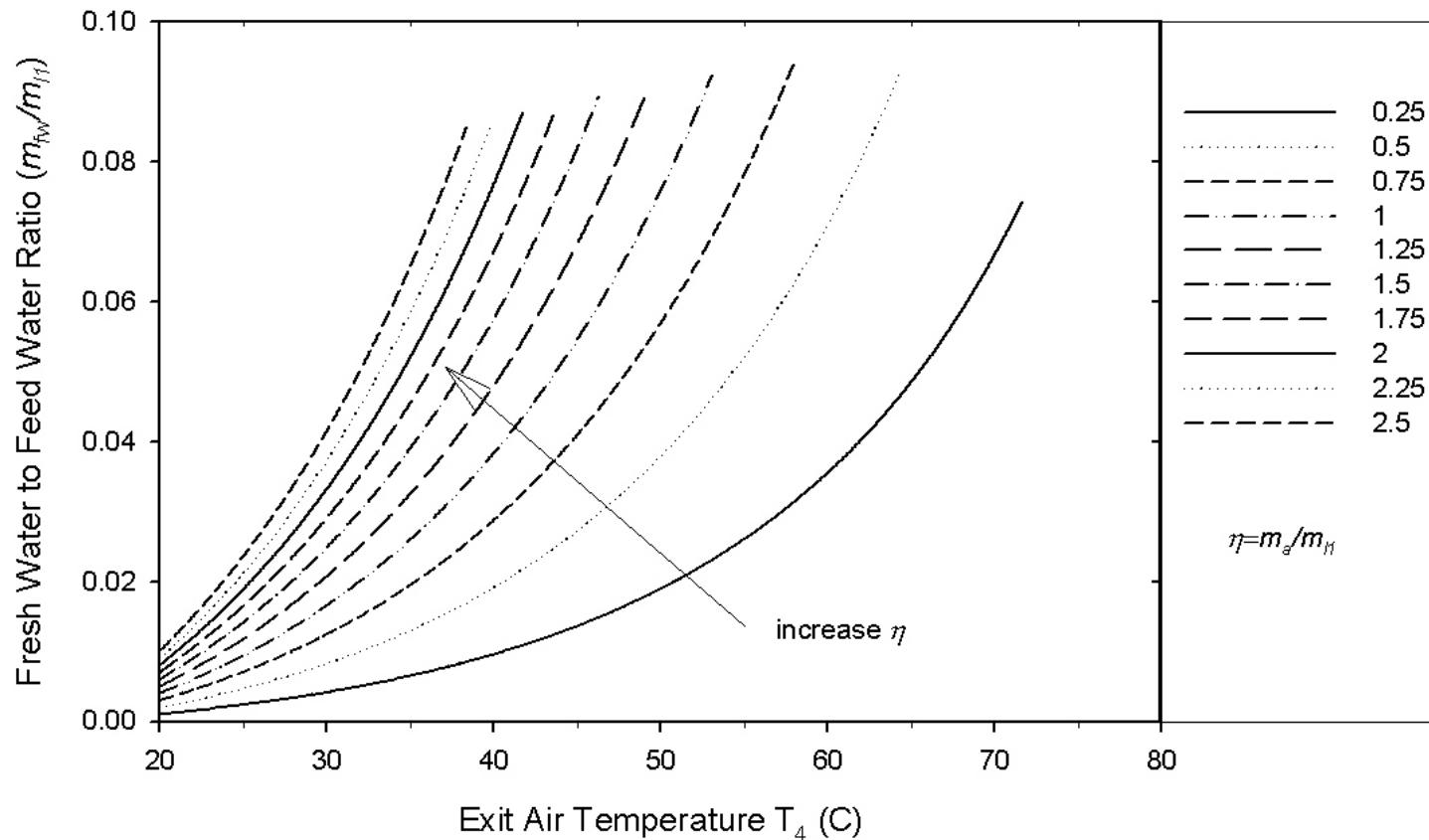


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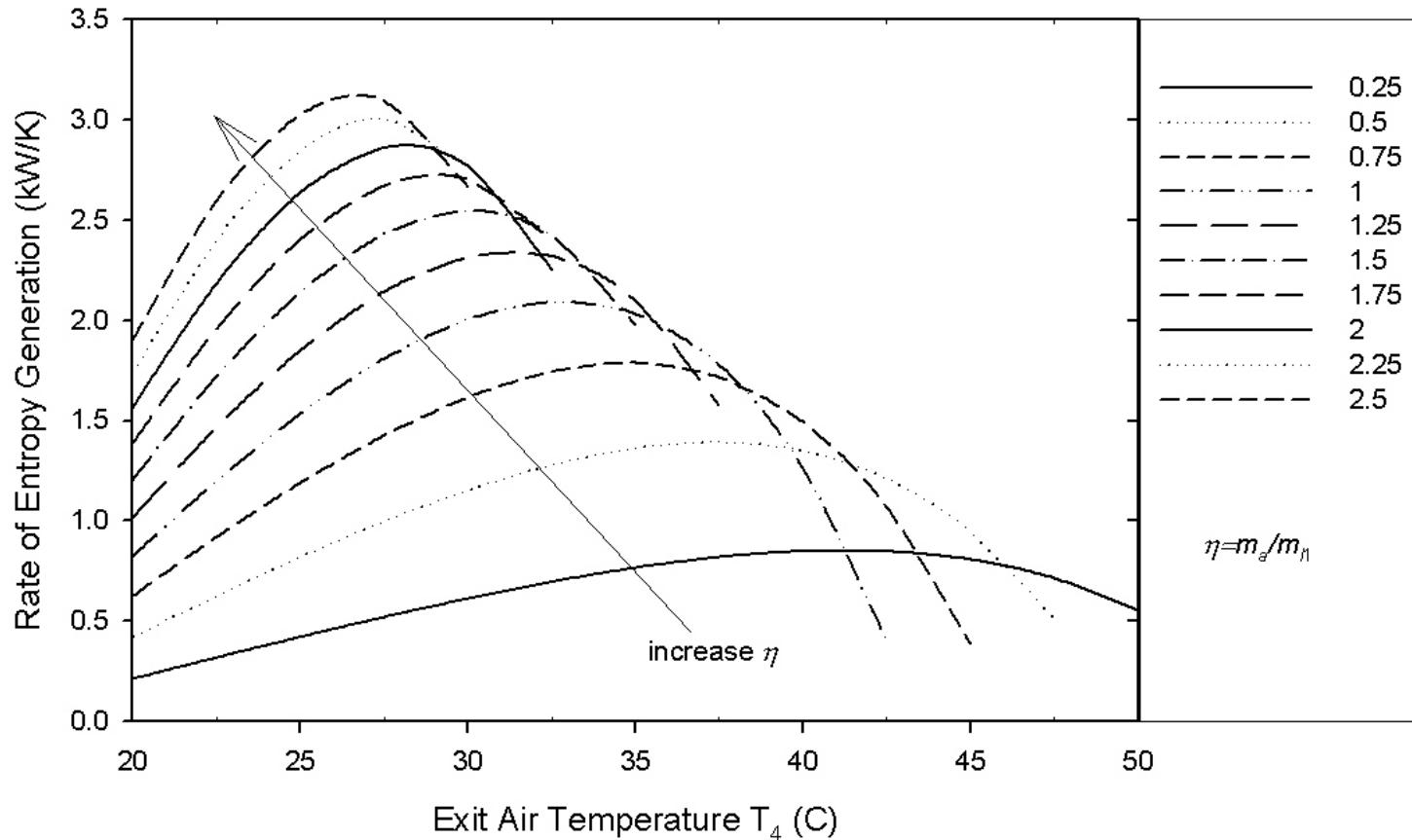
DDD Process Performance

Fresh water production efficiency for $T_H=80^\circ C$



DDD Process Performance

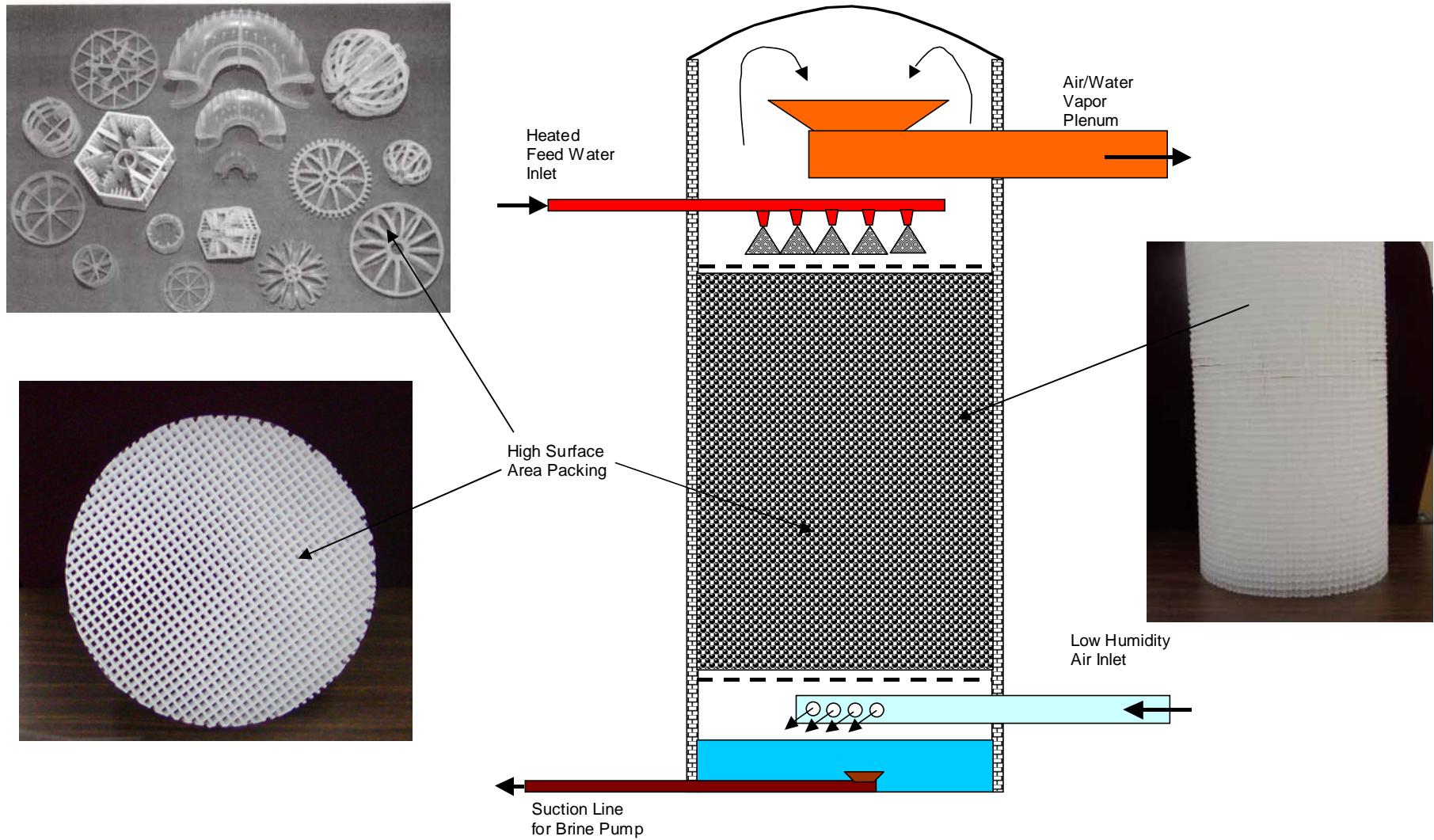
Irreversibility for $T_H=50^\circ C$



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Diffusion Tower Design

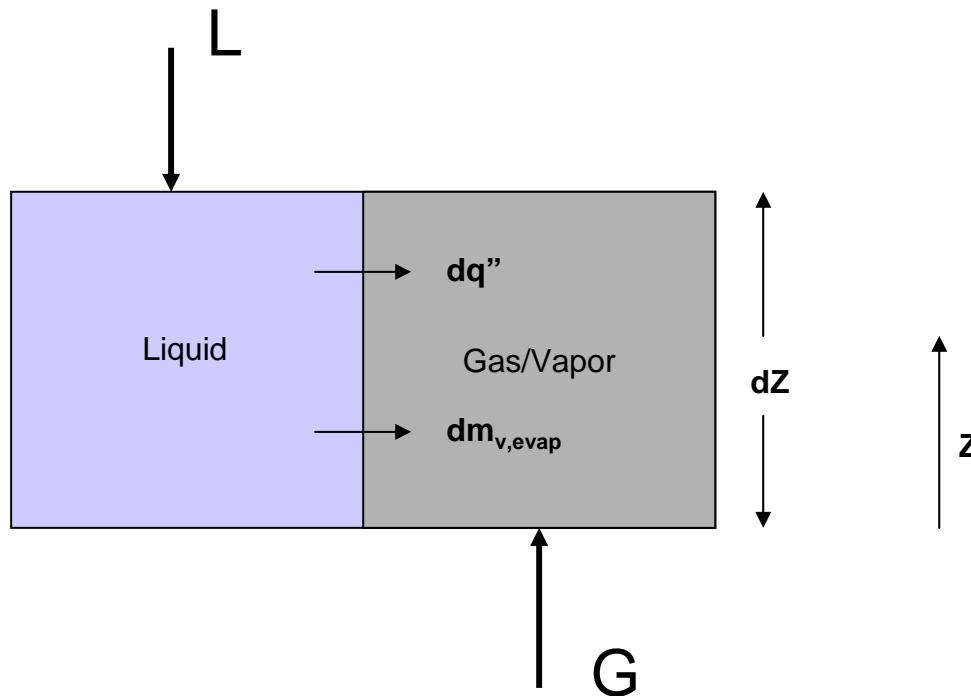


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Diffusion Tower Analysis

- First analysis of cooling towers provided by Merkel (1925)
 - Key assumptions 1) Water mass loss is negligible and
 - 2) the Lewis number is unity
- Merkel analysis not suited for diffusion tower design

Two Film Theory Used to Derive Governing Equations



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Governing Equations

Conservation of Energy--Liquid

$$\frac{dT_L}{dz} = \frac{G}{L} \frac{d\omega}{dz} \frac{(h_{fg} - h_L)}{C_{pL}} + \frac{Ua(T_L - T_a)}{C_{pL} L}$$

Conservation of Energy--Gas/Vapor

$$\frac{dT_a}{dz} = -\frac{1}{1+\omega} \frac{d\omega}{dz} \frac{h_L(T_a)}{C_{p_{mix}}} + \frac{Ua(T_L - T_a)}{C_{p_{mix}} G(1+\omega)}$$



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Governing Equations (cont)

Mass Transfer

$$\frac{d\omega}{dz} = \frac{k_G a_w}{G} \frac{M_V}{R} \left(\frac{P_{sat}(T_i)}{T_i} - \frac{\omega}{0.622 + \omega} \frac{P}{T_a} \right)$$

- Three coupled ODE's; use Runge-Kutta and march in z-direction to solve for T_L , T_a , and ω ; equations require CLOSURE!
- Overall heat transfer coefficient, U , and gas side mass transfer coefficient, k_G must be specified; interfacial temperature, T_i required
- Limited data available on simultaneous heat and mass transfer with water/air through packed beds: McAdams et al. (1949) and Huang and Fair (1989); correlations in DIMENSIONAL form; NOT USEFUL!

Problem Encountered

- We can only measure inlet and exit temperatures, inlet and exit humidities, and mass fluxes
- We cannot measure the interfacial temperature, and thus we cannot directly determine the liquid and gas heat transfer coefficients from measured data



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Determination of Heat and Mass Transfer Coefficients

Resolution 1: Use CFD

Resolution 2: Use Heat and Mass Transfer Analogy

- Onda et al. (1968) correlation used to evaluate liquid and gas mass transfer coefficients; widely tested
- Heat and mass transfer analogy used to evaluate heat transfer coefficients:

$$\frac{Nu_L}{Pr_L^{1/2}} = \frac{Sh_L}{Sc_L^{1/2}} \quad \text{and} \quad \frac{Nu_G}{Pr_G^{1/3}} = \frac{Sh_G}{Sc_G^{1/3}}$$

Liquid side heat transfer coefficient

$$U_L = k_L \left(\rho_L C_{pL} \frac{\kappa_L}{D_L} \right)^{1/2}$$

Gas side heat transfer coefficient

$$U_G = k_G \left(\rho_G C_{pG} \right)^{1/3} \left(\frac{\kappa_G}{D_G} \right)^{2/3}$$

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Determination of Heat and Mass Transfer Coefficients

Interfacial Energy Balance

$$U_L(T_L - T_i) = U_G(T_i - T_a)$$

Evaluation of Interfacial Temperature

$$T_i = \frac{T_L - \frac{U_G}{U_L} T_a}{1 + \frac{U_G}{U_L}}$$

- In practice we find $T_i \sim T_L$



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Determination of Heat and Mass Transfer Coefficients

Onda Correlation (1968)

$$k_L = 0.0051 \text{Re}_{LW}^{2/3} \text{Sc}_L^{-0.5} (ad_p)^{0.4} \left[\frac{\mu_L g}{\rho_L} \right]^{1/3}$$

$$k_G = 5.23 \text{Re}_{GA}^{0.7} \text{Sc}_G^{1/3} (ad_p)^{-2} a D_G$$

$$\# a_w = a \left\{ 1 - \exp \left[- 2.2 \left(\frac{\sigma_c}{\sigma_L} \right)^{3/4} \text{Re}_{LA}^{1/2} \text{Fr}_L^{-0.05} \text{We}_L^{1/5} \right] \right\}$$

This equation was slightly modified from its original form

$$\text{Re}_{LW} = \frac{L}{a_w \mu_L}$$

$$\text{Re}_{GA} = \frac{G}{a \mu_G}$$

$$\text{Re}_{LA} = \frac{L}{a \mu_L}$$

$$\text{Sc}_G = \frac{\mu_G}{\rho_G D_G}$$

$$\text{Sc}_L = \frac{\mu_L}{\rho_L D_L}$$

$$\text{We}_L = \frac{L^2}{\rho_L \sigma_L a}$$

$$\text{Fr}_L = \frac{L^2 a}{\rho_L g}$$



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Diffusion Tower Design and Analysis

1. Specify Inlet Conditions

- Inlet water temperature
- Inlet air temperature
- Inlet relative humidity
- Inlet air and water mass flux

2. Specify Air/Vapor Mixture Design Outlet Conditions

- Outlet water temperature

3. Apply Conservation of Mass and Energy to Liquid and Gas/Vapor Mixture

- Use explicit marching scheme in the direction of the tower height to compute the liquid and vapor temperatures and humidity ratio
- Stop computation when water temperature reaches specified inlet water temperature

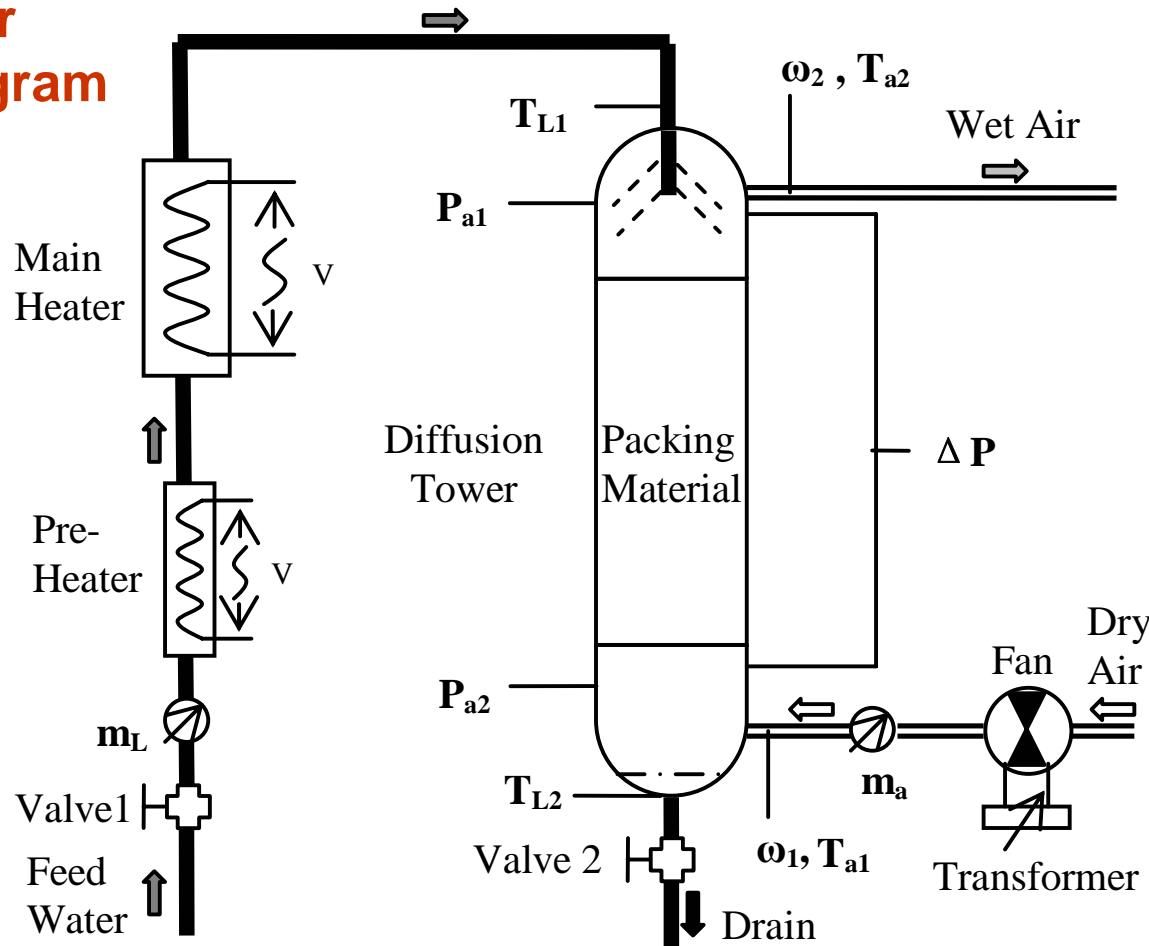


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Experimental Verification of Analysis

Diffusion Tower Schematic Diagram



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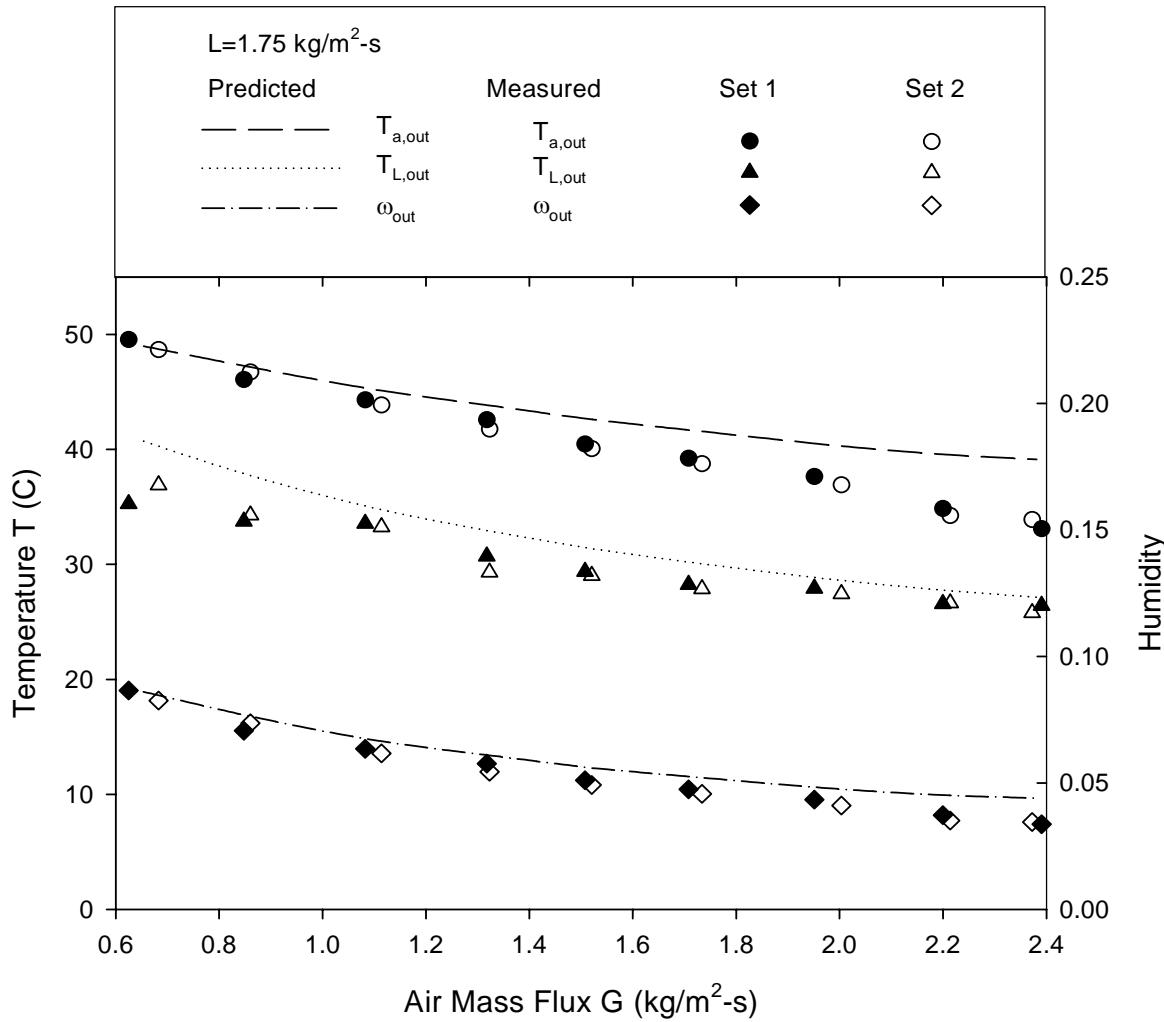
Pictorial View of Diffusion Tower



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Comparison of Model with Experimental Data

Packing -1.8 cm matrix $a = 267 \text{ m}^2/\text{m}^3$ $T_{wi} = 60^\circ \text{ C}$

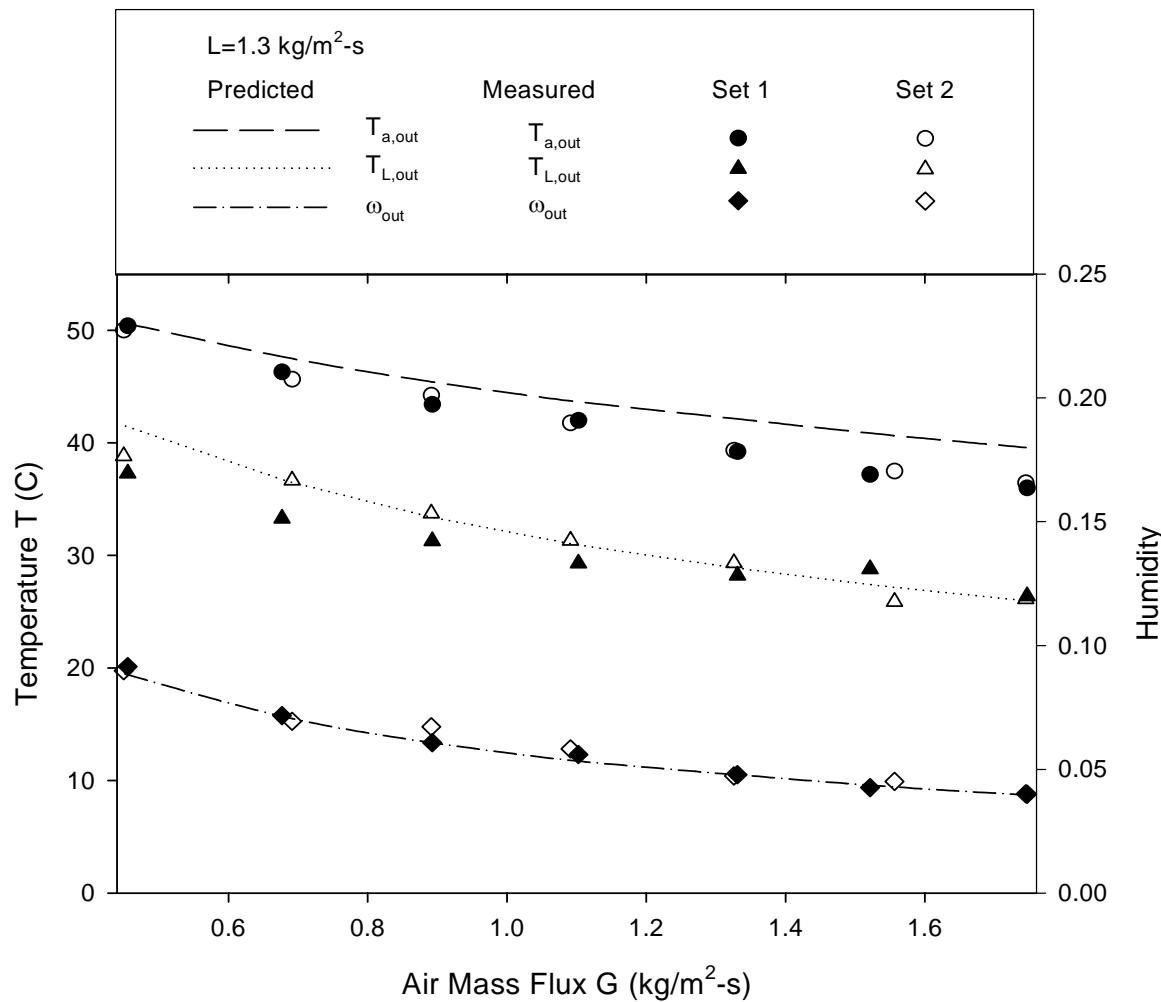


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Comparison of Model with Experimental Data

Packing -1.8 cm matrix a - $267 \text{ m}^2/\text{m}^3$ T_{wi} - 60° C

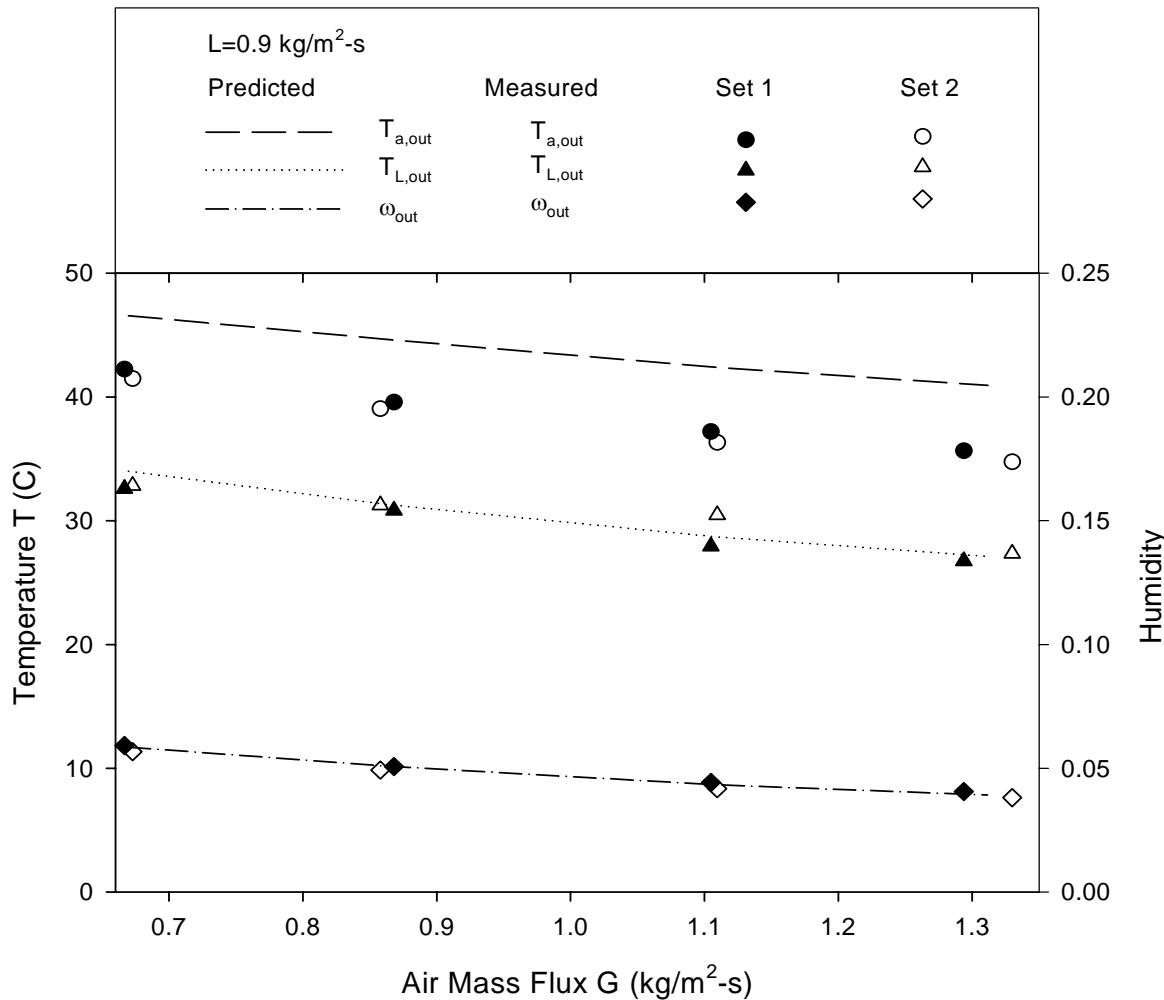


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Comparison of Model with Experimental Data

Packing -1.8 cm matrix a - $267 \text{ m}^2/\text{m}^3$ T_{wi} - 60° C

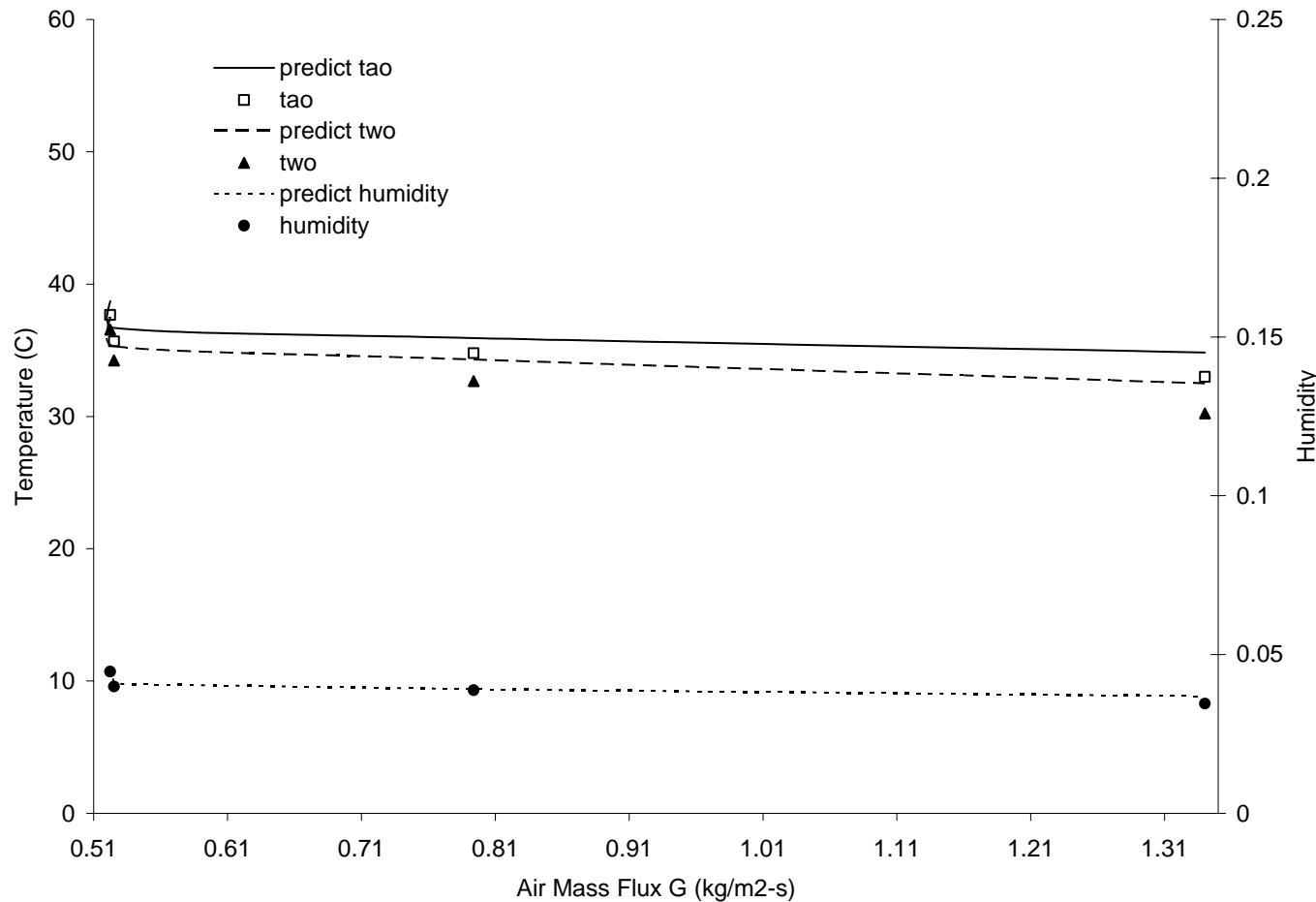


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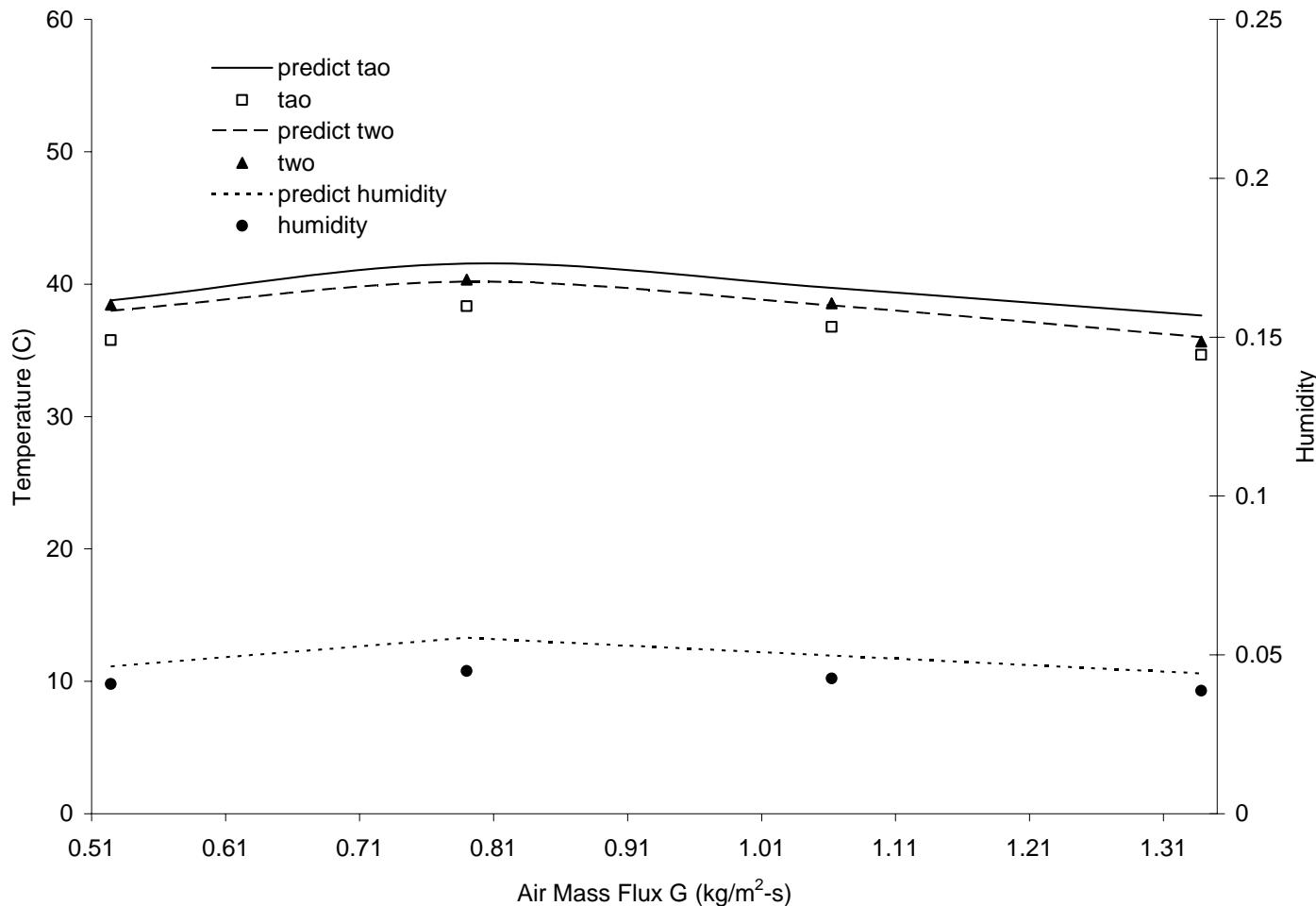
Comparison with Huang and Fair Data (1989)

Packing - 2.54 cm pall rings L- 2.75 kg/m²-s T_{wi} - 40° C



Comparison with Huang and Fair Data (1989)

Packing -2.54 cm raschig rings L- 4.1 kg/m²-s T_{wi}- 40° C

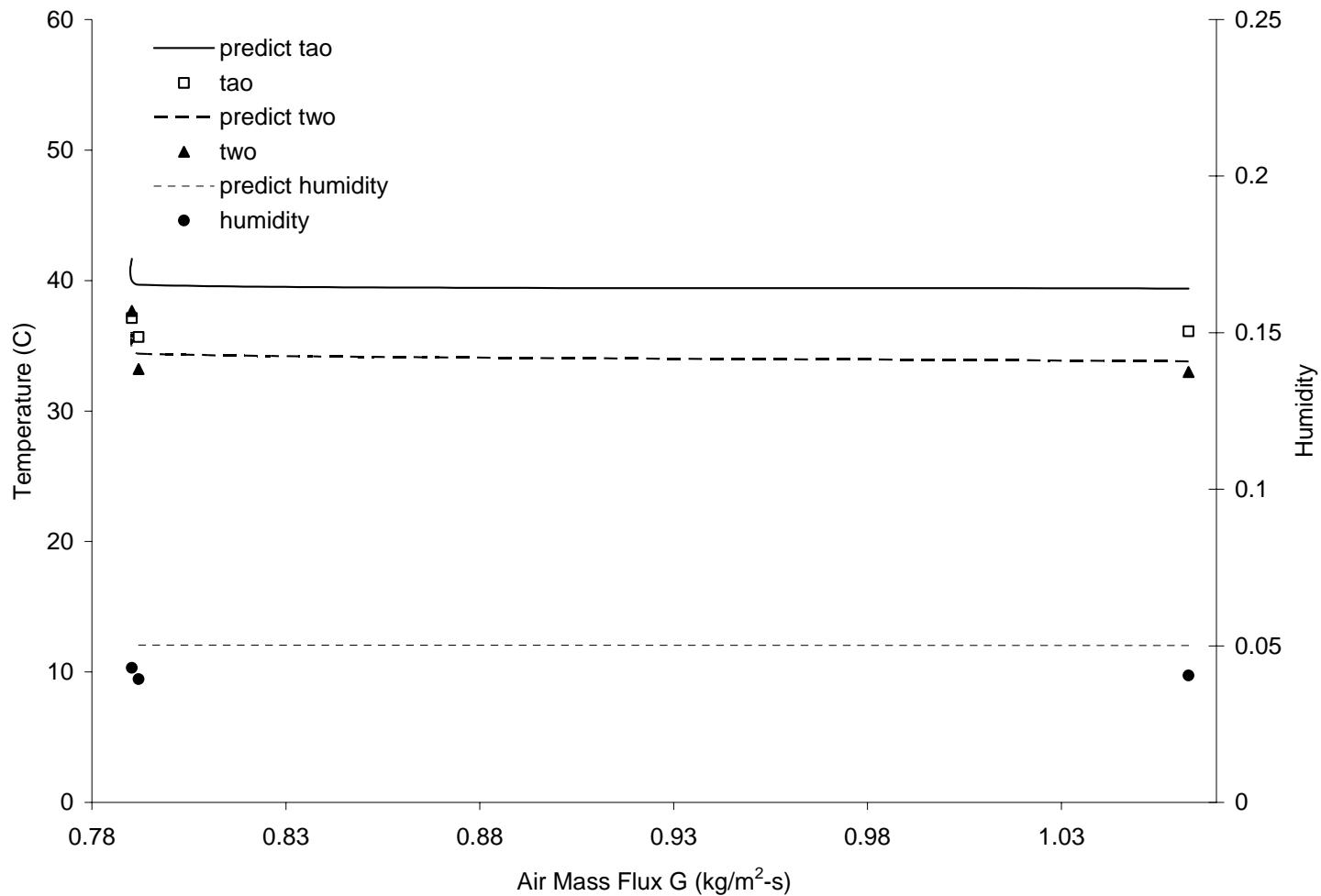


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Comparison with Huang and Fair Data (1989)

Packing - 3.8 cm raschig rings L- 0.77 kg/m²-s T_{wi}- 52° C

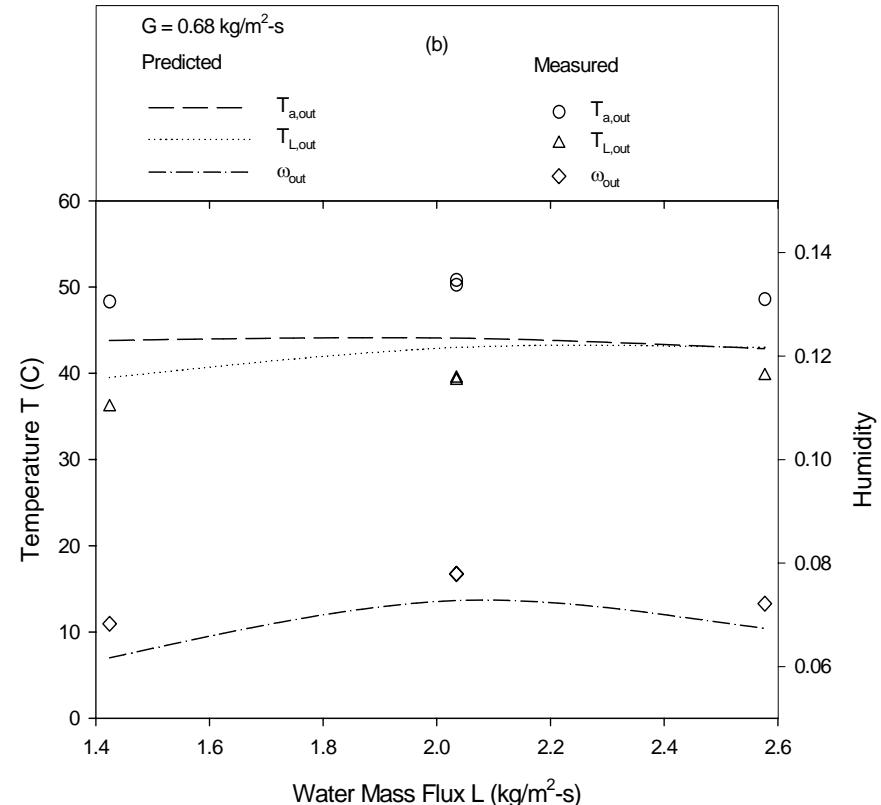
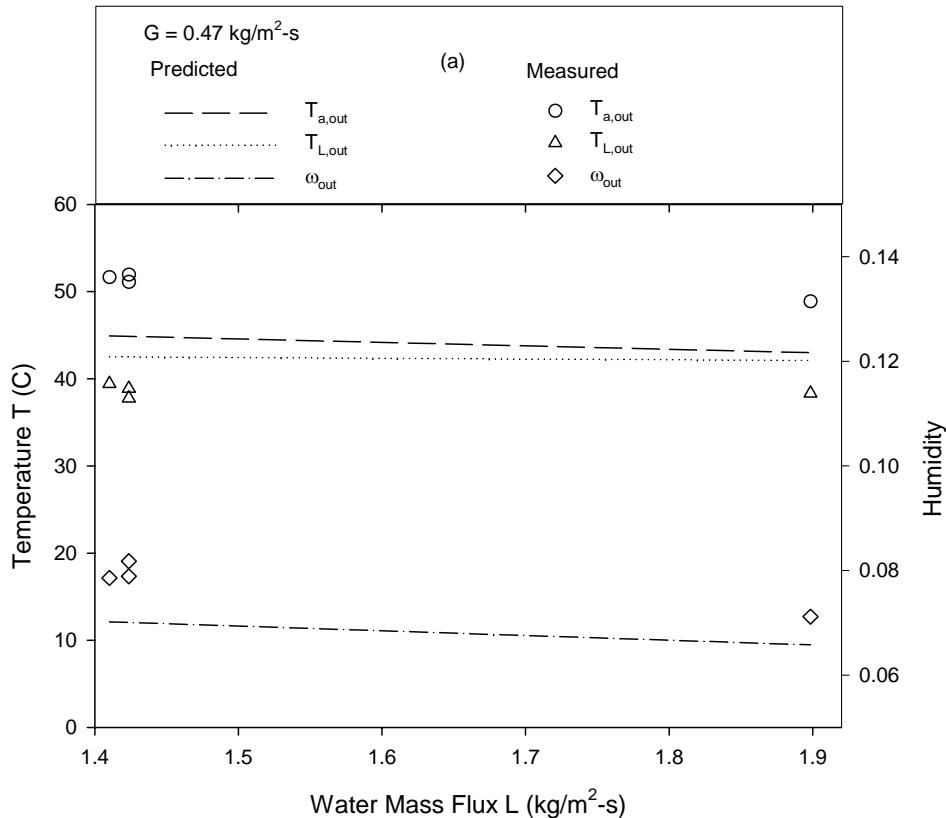


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Comparison with McAdams Data (1949)

Packing -1.5 inch raschig rings L- 0.77 kg/m²-s T_{wi}- 52° C

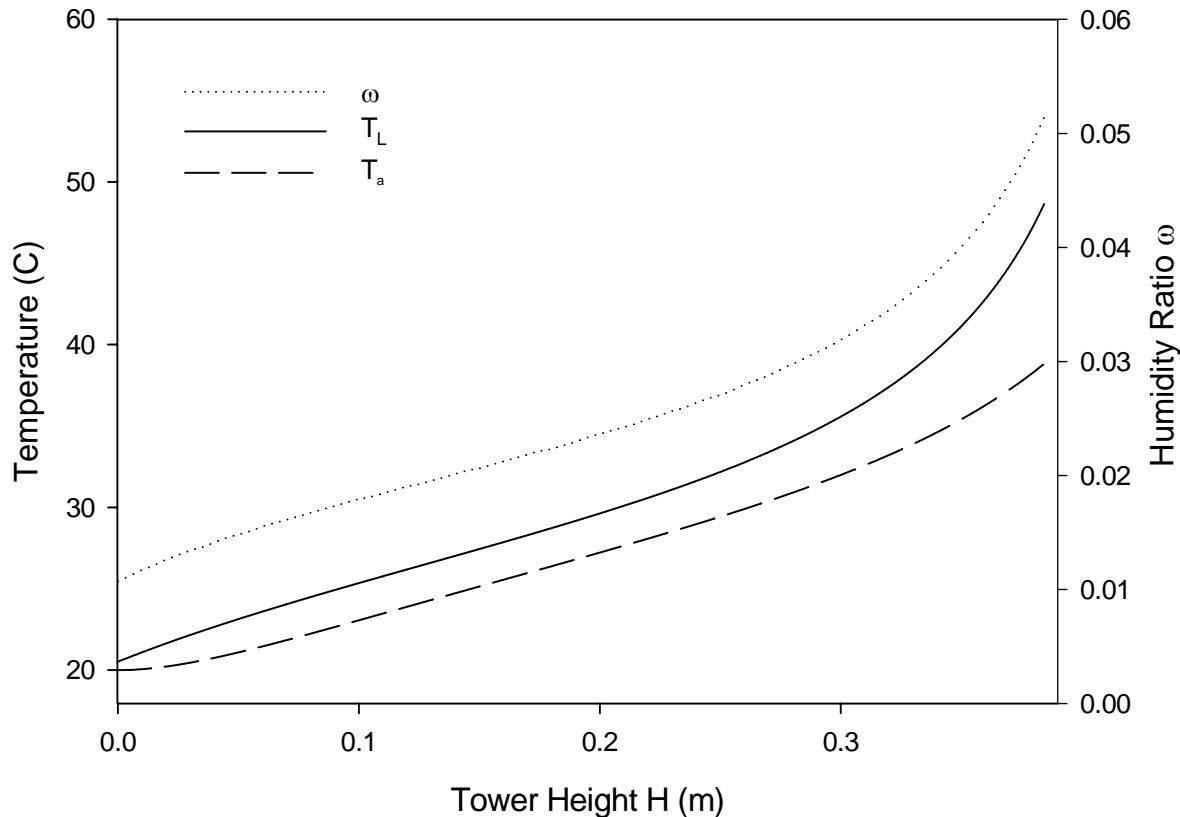


Parametric Study of Diffusion Tower Performance Using Heat and Mass Transfer Model

- Compute required diffusion tower height
- Compute total pumping power for system
- Examine optimum air to water flow ratio
- Estimate cost of fresh water production



Computational Results for Diffusion Tower Design



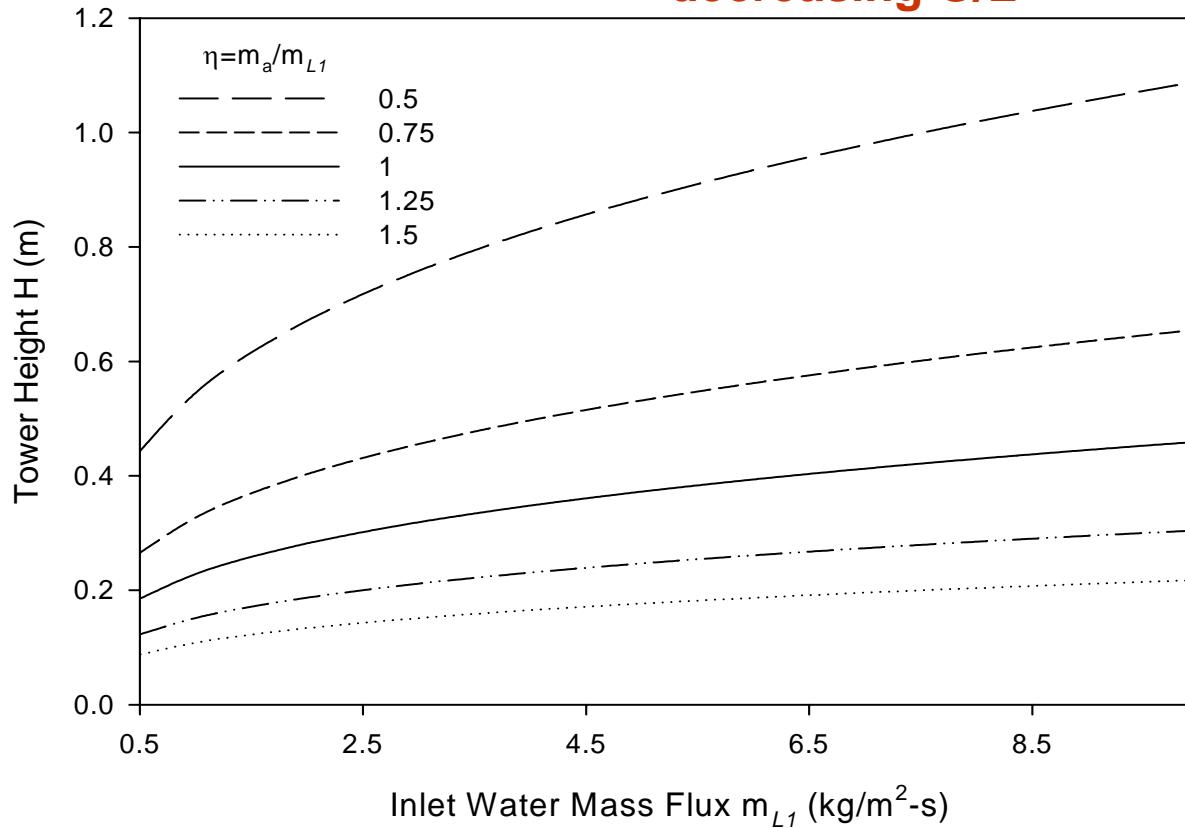
Air and water temperature profiles and humidity profile for $T_{w,I}=50$ C, $L=5$ kg/m²-s, and $G/L=1$



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Computational Results

- Required tower height increases with decreasing G/L



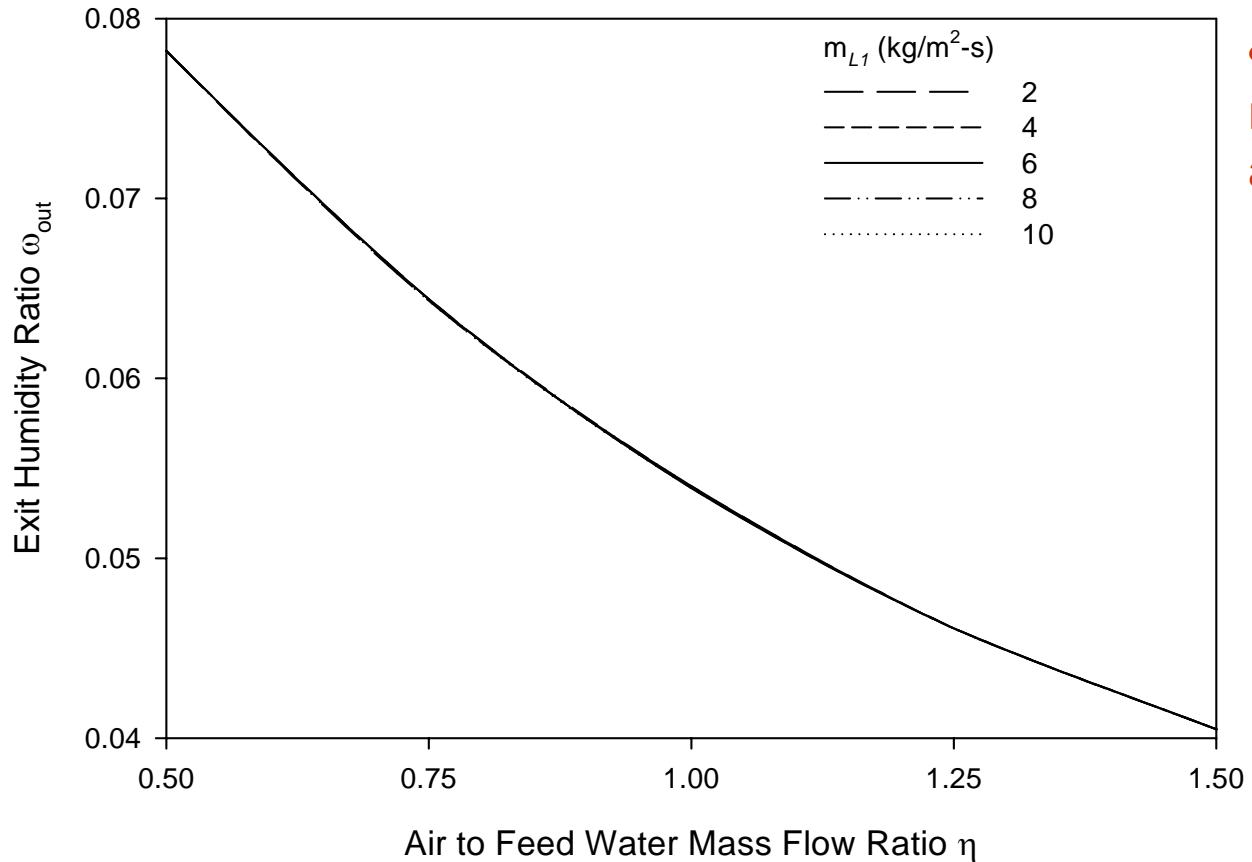
Required tower height for $T_{w,i}=50$ C at different water mass flux and air/water flow ratio



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Computational Results



- Maximum outlet humidity ratio governed by air/water flow ratio

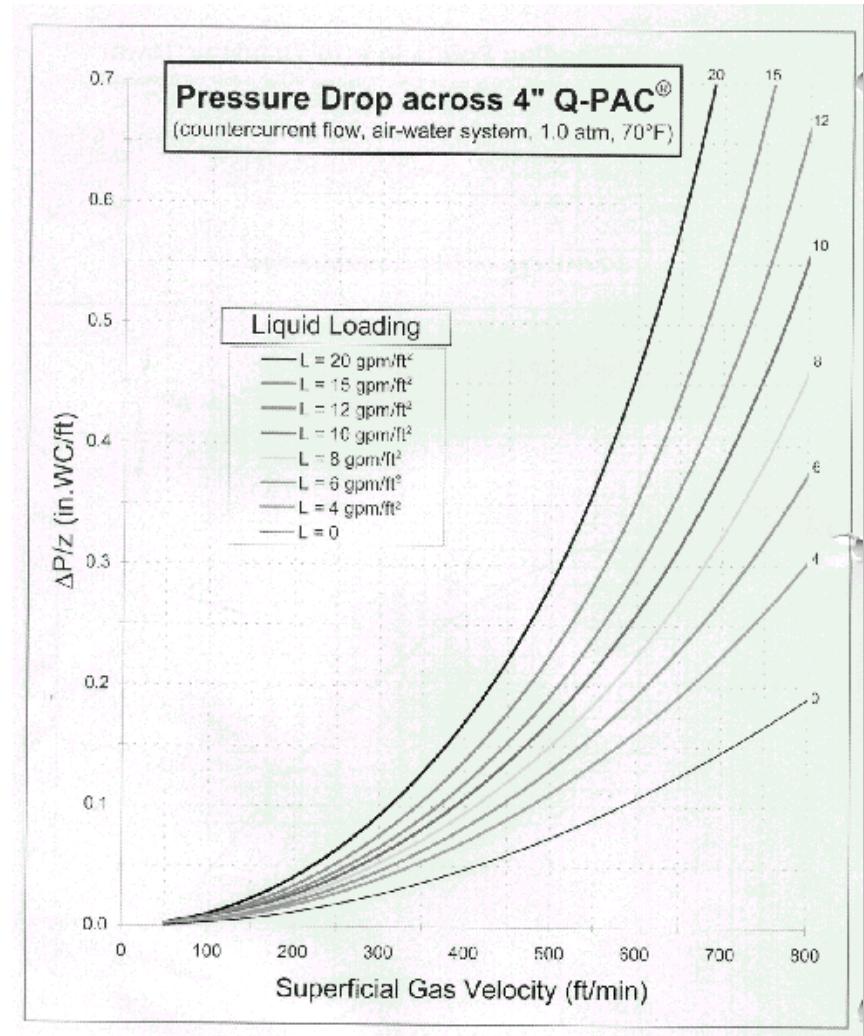
Maximum outlet humidity ratio for $T_{w,i}=50$ C at different air/water flow ratio and water mass flux



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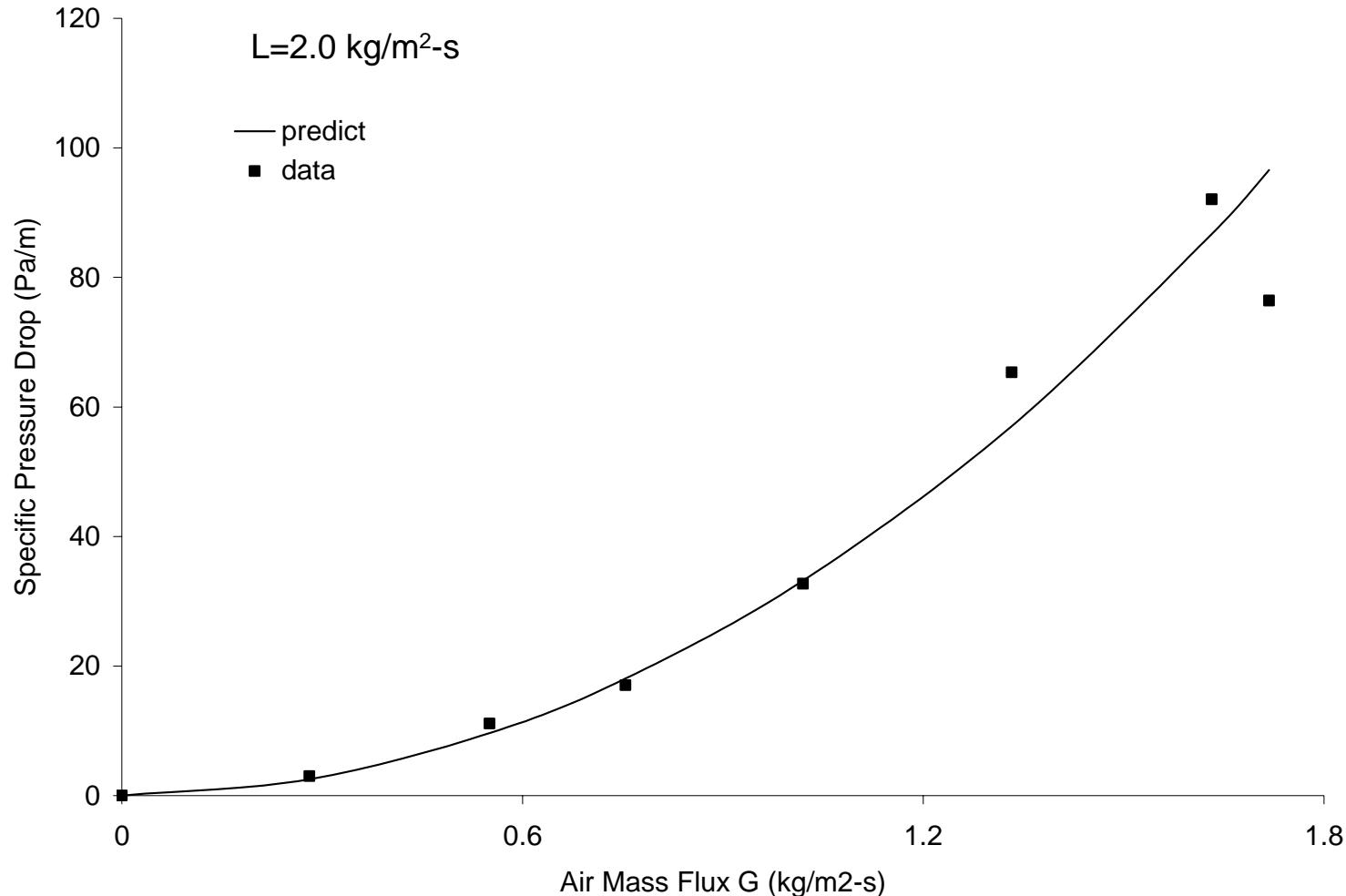
Pumping Power Through Diffusion Tower

- Pressure drop across packing material governs the pumping power
- Optimum tower design which minimizes pumping power exists for each operating condition
- Best design minimizes cost over life-time of operation



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Typical Comparison of Measured & Predicted Pressure Drop



Energy Consumption

Pressure drop on water side

$$\Delta P_L = \rho_L gh$$

Fresh water production rate

$$m_f = GA(\omega_{out} - \omega_{in})$$

Pressure drop on gas side

$$\frac{\Delta P_G}{z} = \frac{G^2}{\rho_G} [0.0354 + 5.05 \times 10^{-5} \left(\frac{L}{\rho_L} \right)^2 + 7.0 \times 10^{-8} \left(\frac{L}{\rho_L} \right)^4 \frac{G^4}{\rho_G^2}]$$

Energy consumption rate

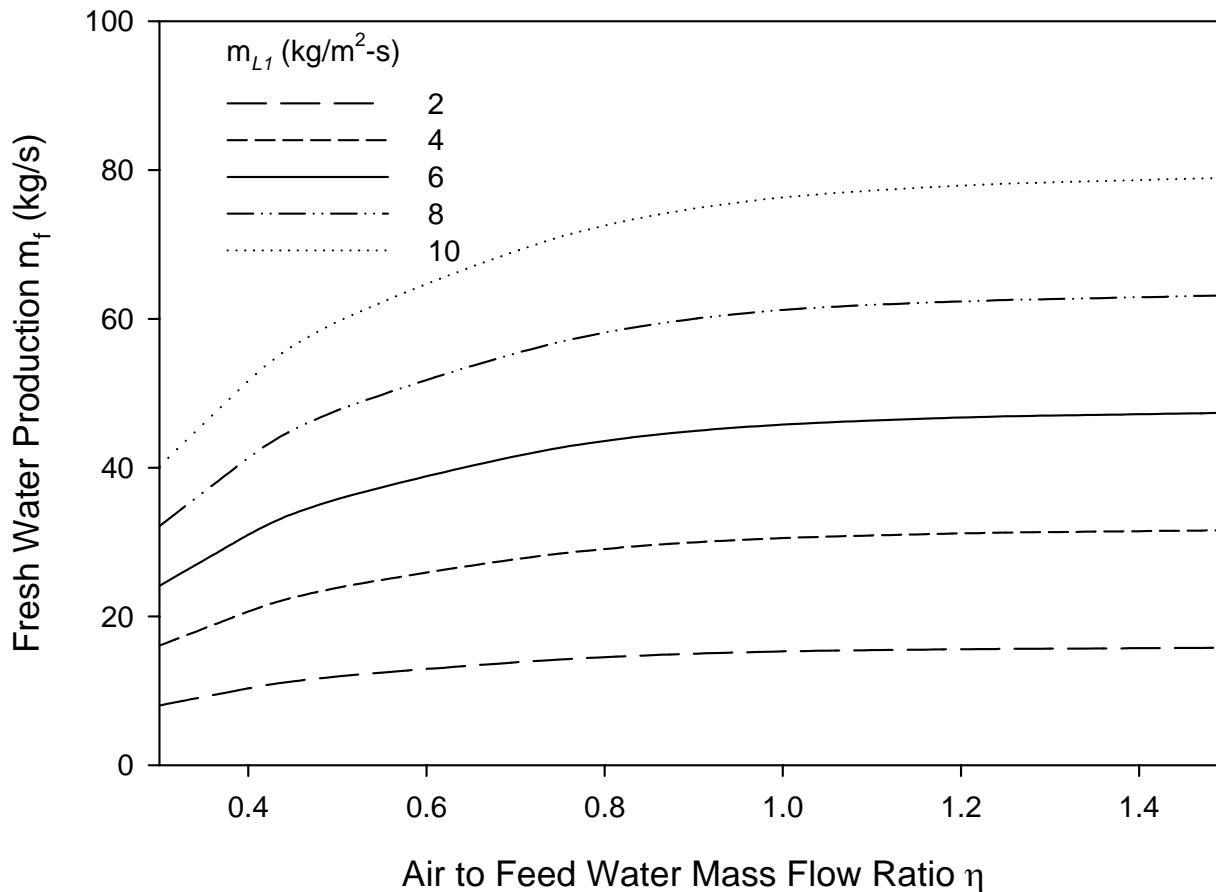
$$E = \frac{LA}{\rho_L} \Delta P_L + \frac{GA}{\rho_g} \Delta P_g$$



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Fresh Water Production



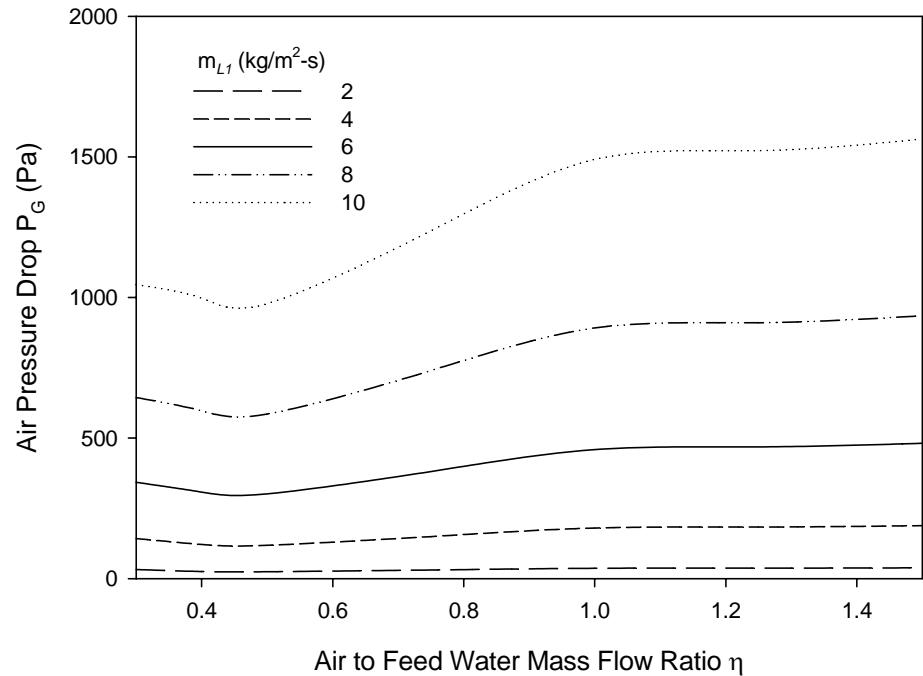
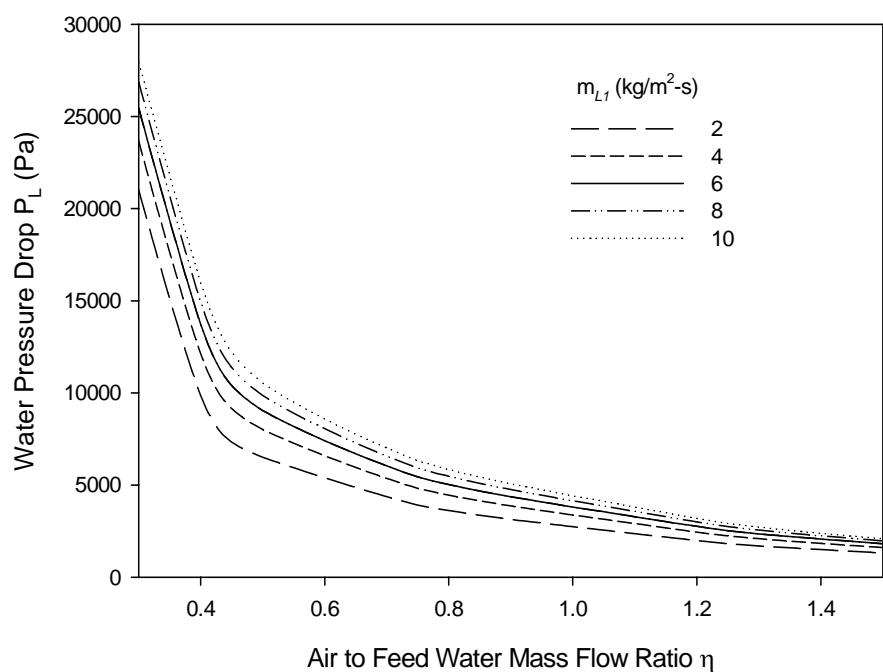
- No gain in fresh water production for $G/L>1$



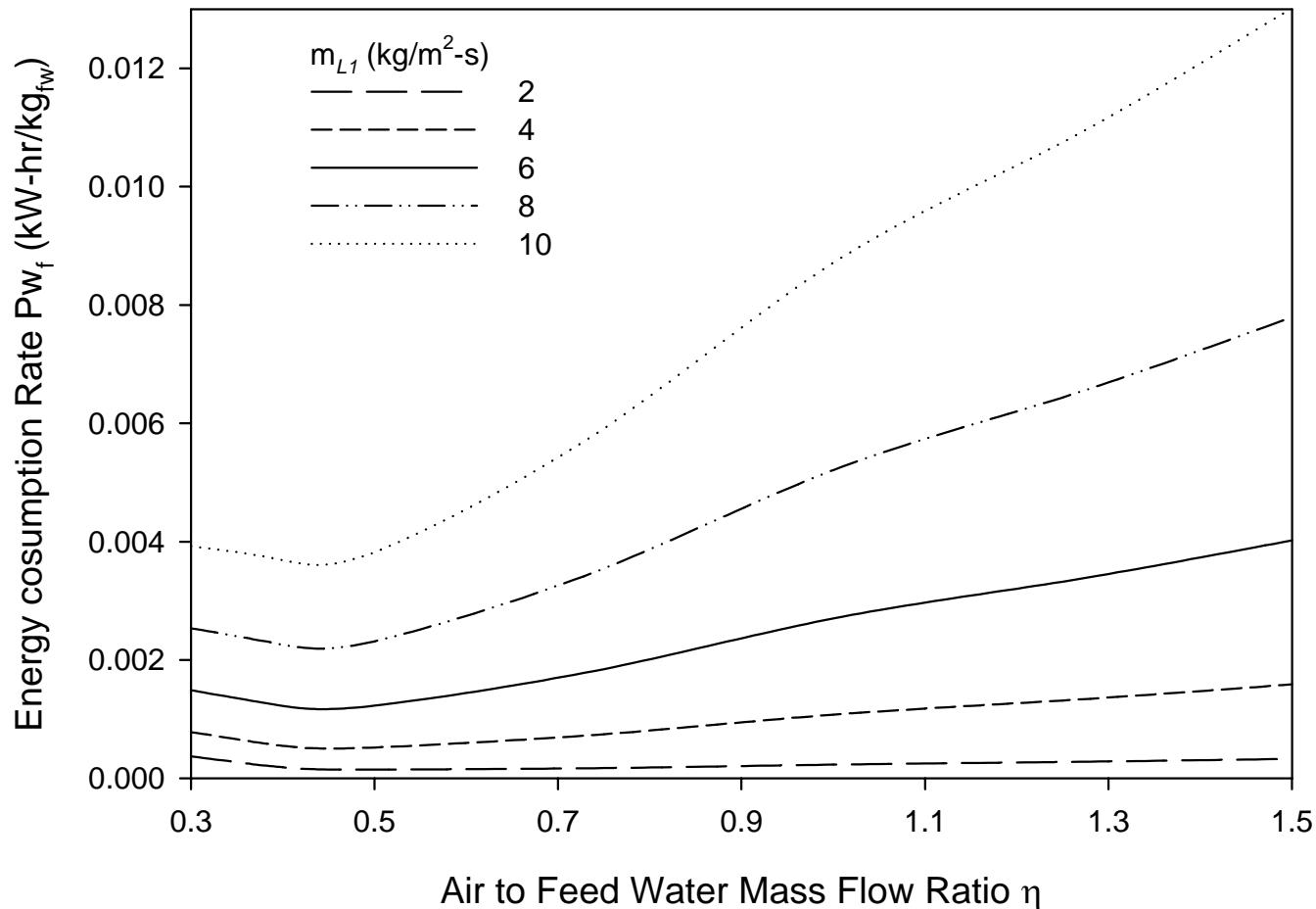
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Pressure Drop

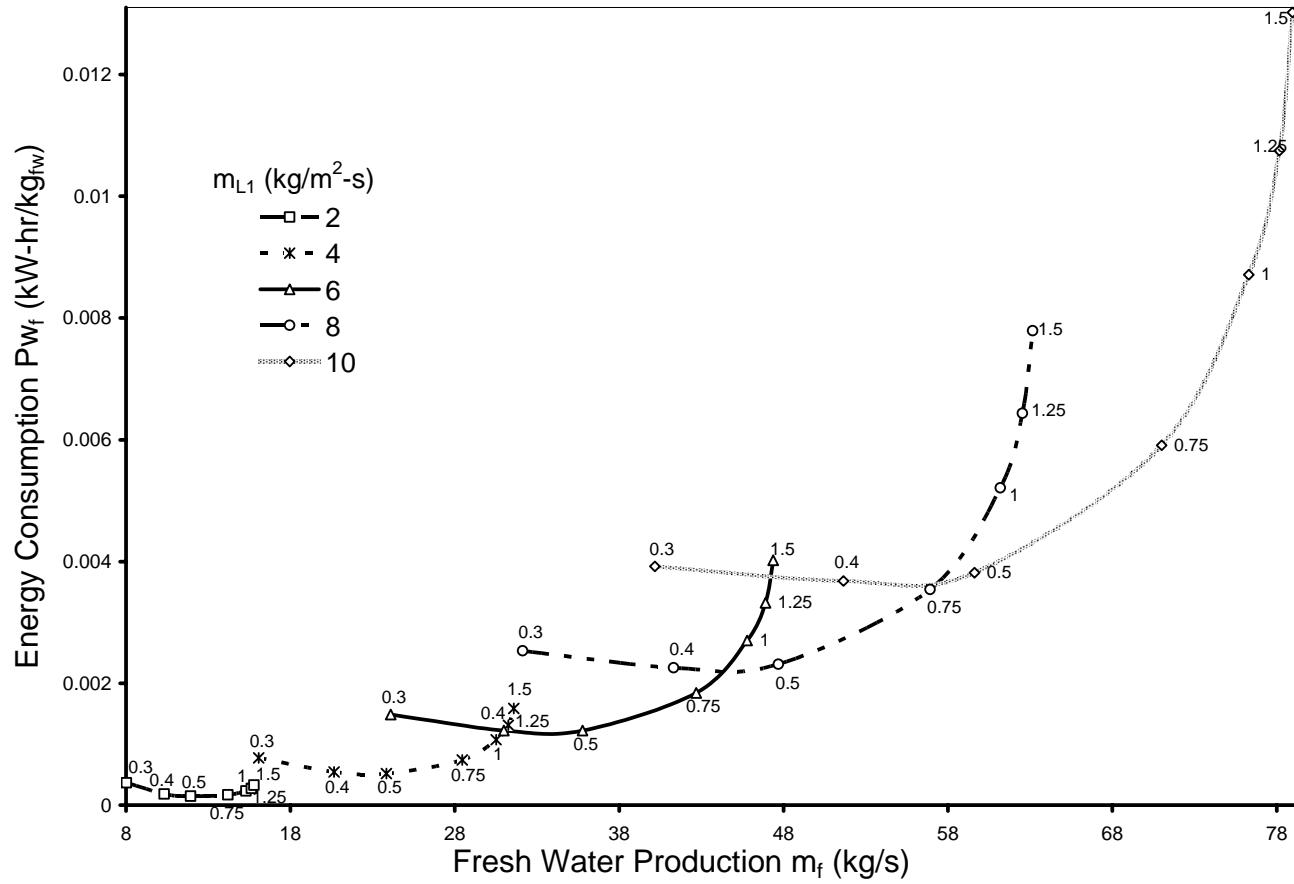


Energy Consumption



Energy Consumption

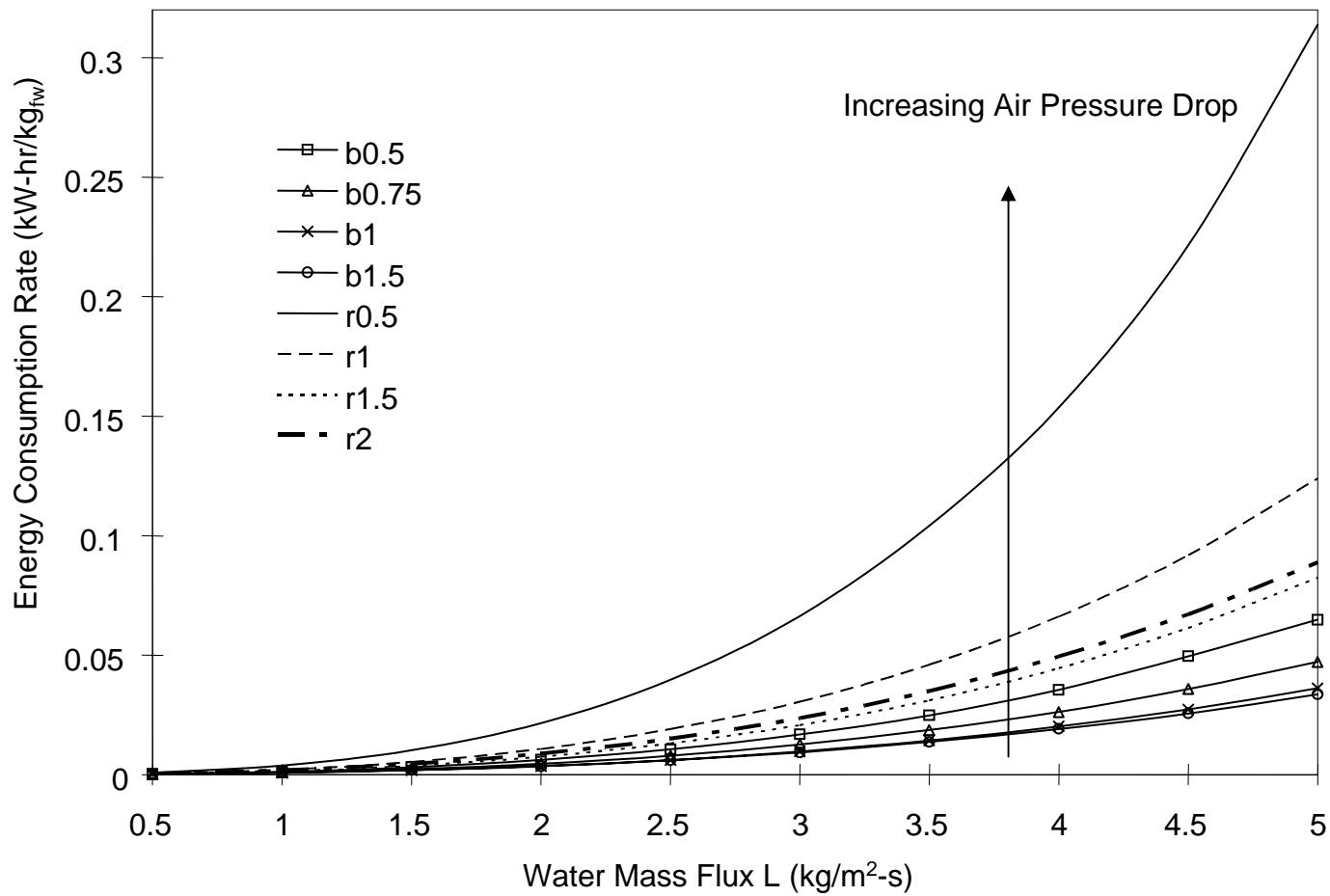
- At 5 cents per kW-h and $E=0.002$ kW-h/kg, the electricity cost for fresh water is 40 cents per 1000 gallons;
CHEAP WATER!



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Energy Consumption



**Energy Consumption Rate for Different Packing Materials
(Air to water mass flow ratio is 0.75)**



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Summary of Diffusion Tower

- A process has been identified that allows the distillation of brackish and seawater at low temperatures
- A design procedure for the diffusion tower has been presented
- For a given feedwater flowrate there exists an air to water flow ratio that minimizes the energy consumption; typically $G/L=0.5$
- At 5 cents per kW-h the energy cost of 1000 gallons of fresh water is typically 40 cents
- Operational water production plant will likely incorporate multiple diffusion towers operating in parallel
- Diffusion towers are small enough that they may be manufactured off-site and delivered on site.



Condenser Design

Laminar Forced Convection Condensation
--Sparrow, Minkowycz, and Saddy (1967)

- Presence of non-condensable gas decreases the interfacial temperature and degrades heat transfer
- Film Condensation not suitable for present application

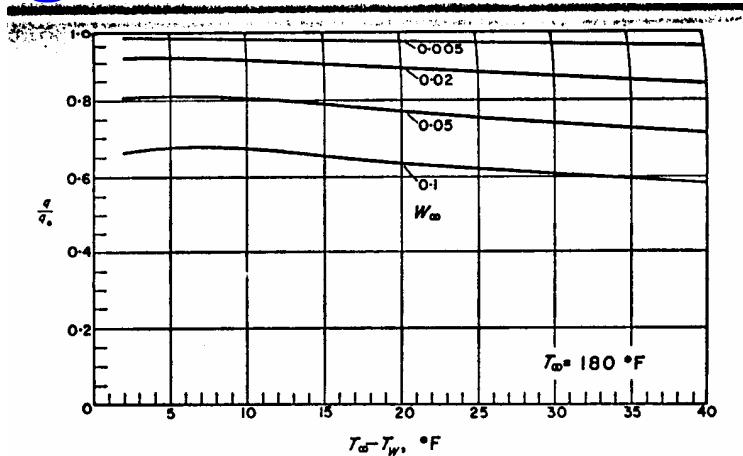


FIG. 5. Condensation heat transfer for steam-air system, $T_\infty = 180^\circ\text{F}$.

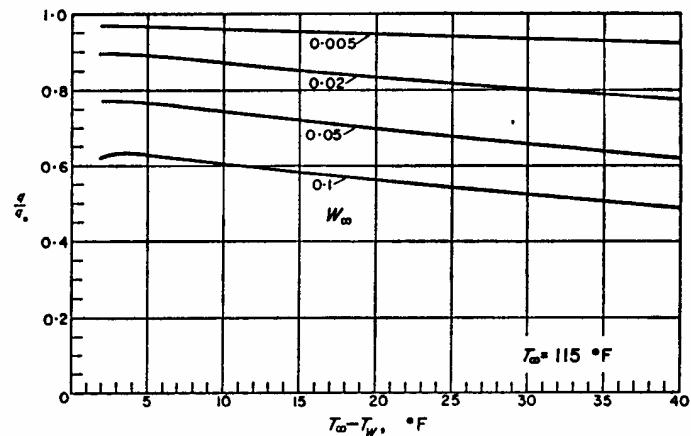


FIG. 7. Condensation heat transfer for steam-air system, $T_\infty = 115^\circ\text{F}$.



Condenser Design

- Direct contact condensation required for air/water mixtures
- Extensive experience gained in design of Ocean Thermal Energy Conversion, Hawaii (OTEC)
- Design procedure specified by,
D. Bharathan, B.K. Parsons, and J.A. Althof,
“Direct-Contact Condensers for Open-Cycle OTEC Applications,” SERI/TP-252-3108, US DOE National Renewable Energy Laboratory.

- Graduate Students Currently Working on Design and Analysis

Analysis: VENUGOPAL JOGI

Design: LI YI



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Condenser Design for DDD Process

- Double column
co-current and
counter current
process



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Fouling Prevention

- Commercially available chlorinators will prevent the growth of marine micro- and macro-organisms such as algae, mussels, and barnacles



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Comparing Desalination Technologies[‡]

[‡]Averaged data obtained from California Coastal Commission Report, 1992

Technology	Cost \$/1000 gal	Energy Consumption kW-hr/kg	
		Elect.	Therm.
DDD	1.00	0.002	0.75
MSF	9.77		0.025
RO	3.00		0.007
Florida North-South Pipeline (300 mi, 10 mil gpd, 20 inch diameter)			0.003



Technology	Advantages	Disadvantages
DDD	<ul style="list-style-type: none"> •Low energy consumption and low cost water production •Waste heat utilized •Low salinity concentration discharge-minimal environmental impact •Low maintenance required •Low temperature operation--low cost of construction and packing replacement 	<ul style="list-style-type: none"> •Lower conversion efficiency
RO	<ul style="list-style-type: none"> •Feed water does not require heating •Lower energy requirements •Removal of unwanted contaminants such as pesticides and bacteria 	<ul style="list-style-type: none"> •High maintenance required •Performance degrades with time •High salinity concentration discharge-environmental impact •High cost of filter replacement •Generates waste from pretreatment and backwash
MSF	<ul style="list-style-type: none"> •Large production rates and economies of scale •Continuous operation without shutting down 	<ul style="list-style-type: none"> •Large energy consumption •High cost of water production



Thermodynamic Realities

- Main condenser operating pressure is typically 10 kPa absolute
- Corresponding water saturation temperature is approximately 45°C
- Highest expected cooling water temperature out of condenser is expected to be 40°C
- Current steam power plants in U.S. design main condenser for about a 6°C temperature rise of cooling water



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Further Development of DDD Technology

- A seemingly inexpensive process for distilling large quantities of water has been developed
- A design and optimization procedure for the diffusion tower has been developed
- Design and analysis procedure for efficient condensation required
- Discussions with FPL to fabricate a pilot plant in Ft. Meyers, Florida are ongoing

